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Experimental Results on a Single-Material Optical Fiber

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Experiments confirm a number of theoretical predictions regarding the behavior of single-material optical fibers. In particular, the predicted modal velocity spread (10's of ns/km) and the numerical aperture are found to be in good agreement with theory.

I. INTRODUCTION

The concept of optical fibers made from a single material was the subject of a recent article;[1] the advantages of such fibers are their construction of low-loss fused silica and their freedom from the problems associated with glass interfaces. In this paper, we present experimental results on the dispersion observed in a *particular* single-material fiber. The significance of this work lies in the good agreement between the theory and the experiment; the results do not represent a careful evaluation of single-material fiber as a transmission medium.

The results of the experiments are as follows:

(*i*) The predicted modal velocity spread was confirmed.
(*ii*) The measured numerical aperture is directly proportional to wavelength, as predicted by theory.
(*iii*) There was very little mode coupling between lowest order modes for lengths up to 100 meters.
(*iv*) Penetration of energy into the support structure was small (the decay constant is about 20 dB/μm).

II. THEORY OF MODAL VELOCITY SPREAD

The theory of single-material fibers is summarized in Ref. 1. In the present discussion, we concentrate on the modal dispersion of such fibers. Given the structure shown in Fig. 1, we assumed that the electromagnetic fields vary either sinusoidally or exponentially along

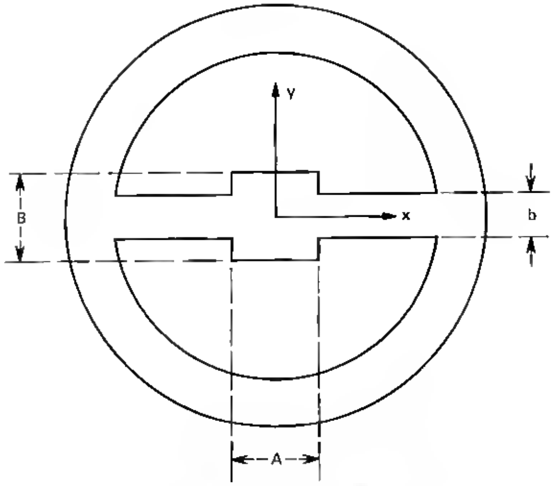

Fig. 1—Idealized fiber cross section.

x, y, and z. We further assume the modes of interest to he far ahove cutoff so that the transverse wave numhers can he considered to he constant; we approximate them as

$$k_x = \frac{\pi\mu}{A} \tag{1}$$

and

$$k_y = \frac{\pi\nu}{B}. \tag{2}$$

A and B are defined in Fig. 1 and μ and ν are the mode orders. It then can he shown that the group velocity of the mode of order $\mu\nu$ is approximately

$$V_{g_{\mu\nu}} = \frac{c}{n}\left\{1 - \frac{\lambda^2}{8n^2}\left[\left(\frac{\mu}{A}\right)^2 + \left(\frac{\nu}{B}\right)^2\right]\right\}. \tag{3}$$

This gives for the expected time spread hetween the fastest and the $\mu\nu$ pulses

$$\Delta\tau_{\mu\nu} \simeq \frac{L\lambda^2}{8cn}\left[\left(\frac{\mu}{A}\right)^2 + \left(\frac{\nu}{B}\right)^2\right], \tag{4}$$

where L is the fiher length. From Ref. 1, the maximum value of the hracketed term in eq. 4 is b^{-2}; b is defined in Fig. 1. Thus, the maximum time spread between pulses is

$$\Delta\tau_{\max} = \frac{L}{8cn}\left(\frac{\lambda}{b}\right)^2. \tag{5}$$

III. EXPERIMENTAL RESULTS

3.1 Description of the fibers

The fibers used for our experiments were made of fused silica and had the cross section shown in Fig. 2. Because of the multimode nature of this particular fiber, we anticipate that the theory developed in Section II for the rectangular fiber geometry will still approximately apply.

The following numerical result can serve as a guide in predicting the actual measurement. Assume a fiber with $A = B = 10$ μm, $b = 2$ μm, and $n = 1.46$, and let $\lambda = 1$ μm. Then,

$$\Delta\tau_{\mu\nu} = 2.85L(\mu^2 + \nu^2)ps. \tag{6}$$

For a 100-meter fiber length, the low-order pulses would have time separations of a few tenths of a nanosecond. This implies the following: if such a fiber were excited by a pulse whose width is small compared to $\Delta\tau_{\mu\nu}$, then, assuming little mode coupling, each mode should be

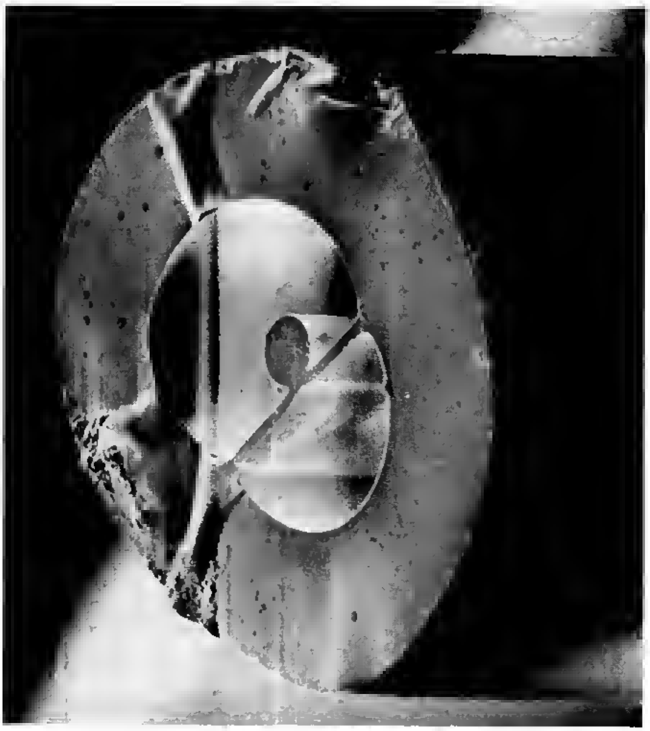

Fig. 2—Photograph of experimental fiber cross section.

observable at the fiber output, providing, of course, that the detection system is sufficiently broad band.

3.2 Dispersion

In the experiments, a mode-locked Nd:YAG laser was used as the source. Using a germanium photodetector, this system yields detector-limited output-pulse widths of less than 200 ps.[2] An early observation was that energy incident in a single input pulse appears at the fiber

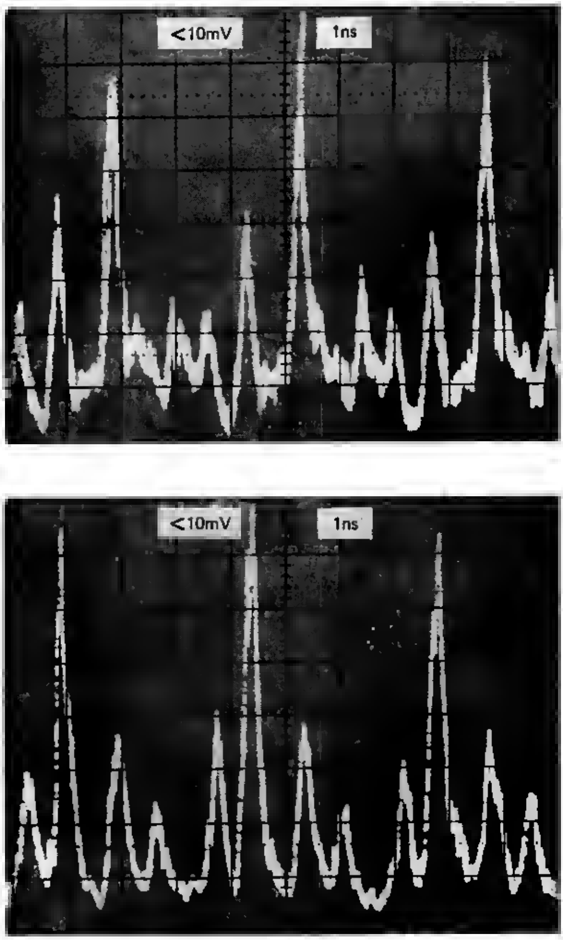

Fig. 3—Fiber output as a function of time and launching conditions.

output as several pulses each representing a mode group. (In this case the fiber was about 90 meters long.) The relative amplitudes of the output pulses could be changed by varying the input launching condition, which is demonstrated by the two photographs shown in Fig. 3.

Additional information was obtained by measuring the velocity difference between the output pulses as a function of fiber length; Fig. 4 shows the results for the first few modes. The results are in reasonable agreement with that predicted by eq. 4; the predicted time spread between the first four modes is 8 ps/m, 17 ps/m, and 21 ps/m, whereas the measured values were 7 ps/m, 16 ps/m, and 22 ps/m. Note that the time difference approaches zero for zero length, which suggests little mode coupling among the lower-order modes as does the previous observation that individual modes could be preferentially excited. Although not shown, the higher-order modes behave differently, having a time difference which appears to be related to the lower order modes. This suggests that the higher-order modes are possibly generated by mode coupling from the lower-order modes and that the higher-order modes suffer more loss.

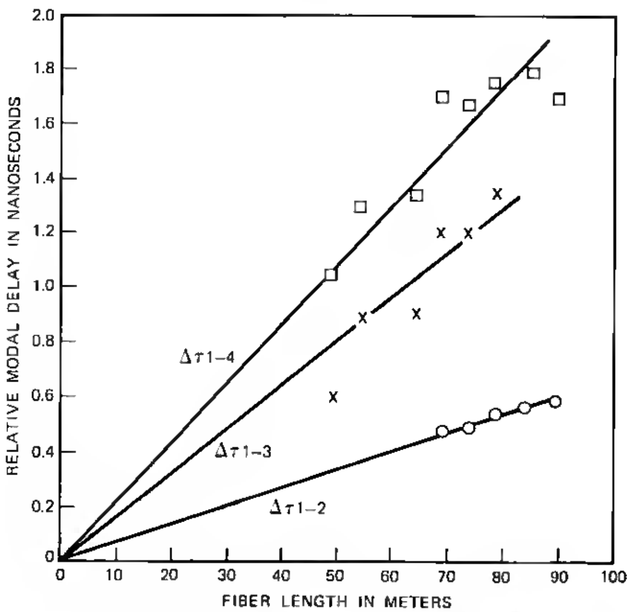

Fig. 4—Relative modal delay as a function of fiber length.

3.3 *Numericel aperture*

Theory predicts a numerical aperture (half-angle of the fiber radiation cone) of NA $= \lambda/2b$. For our fiber, b was 2 μm so that the theoretical NA at $\lambda = 1.06$ μm was 0.265, and at $\lambda = 0.6328$ μm the NA should be 0.1582. The predictions compare favorably with our measured results, which were 0.27 at $\lambda = 1.06$ μm and 0.16 at $\lambda = 0.6328$ μm as determined from the angular spread of the far field radiation.

IV. SUMMARY

The experimental investigation of the dispersion in a single-material optical fiber showed good agreement with theory. The linear dependence of numerical aperture on wavelength also was verified.

V. ACKNOWLEDGMENTS

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